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TRANSMISSION LINE DESIGN FOR A POWER DISTRIBUTION SYSTEM AT 20 KHz FOR AIRCRAFT

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1.0 INTRODUCTION

The purpose of this work is to design a transmission line for a power distribution system in aircraft. The line is to operate at 20 kHz, have very low inductance and, consequently, a low characteristic impedance; it must withstand 440 V at an altitude of 15 km (50 000 ft) and 1 kV at 300 km (about 100 000 ft), and must be capable of carrying 100 A. The connectors and supports must have a minimum creepage path of 0.635 cm (1/4 in.).

Additional considerations of the line design include connectors for parallel loads, number of such connectors, mechanical strength and heat dissipation, dc resistance, and weight.

The fundamental problem in determining the inductance per unit length, and the characteristic impedance of the line is the calculation of inductance or capacitance because $LCv^2 = 1$, with L and C representing the inductance and capacitance per unit length, respectively; and v representing the velocity of wave propagation along the line (in the case of the fundamental mode, the TEM mode, the velocity is governed by the properties of the material between the wires). At a frequency of 20 kHz, the skin depth for copper (resistivity $1.7 \times 10^{-8} \Omega\text{-m}$ conductivity $= 5.88 \times 10^7 \text{ mho/m}$) is 0.46 mm \approx 0.5 mm, and the wavelength in free space, is 15.0 km and about 9.0 km in many commercially used insulating materials (relative dielectric constant on the order of 3). Thus, the total length of the line is on the order of 0.02 to 0.033 wavelength which justifies the quasi-static approximations (refs. 1 to 5). The close spacing among the individual conductors strengthen the validity of the relation $LCv^2 = 1$ and of the "quasi-TEM" mode dominance. [Strictly speaking, the TEM mode in this case is not absolutely pure because of two factors: there are two dielectrics between the wires, the insulation and air; and the wires are lossy. As a consequence, there will be an axial component of the electric field, but it is so small that the assumption about TEM is more than satisfactory for practical purposes. Furthermore, with reasonable insulation the shunt conductance (between the wires) will be on order of 10^{-17} mho/m (ref. 6). As a consequence, the term $RG/\omega^2 LC$ will be on the order of $10^{-14} \ll 1$, so that the propagation constant will very nearly be equal to $\omega\sqrt{LC}$, so that the relation $LCv^2 = 1$ will be satisfied in any practical system.]

The SI system of units will be used throughout this report.

2.0 DETERMINATION OF PARAMETERS

2.1 Introduction

In order to design a suitable transmission line, several parameters need to be determined for different configurations. The parameters are L , the inductance per unit length; C , the capacitance per unit length; Z_0 , the

characteristic impedance; and R , the resistance per unit length. (G , the shunt conductance per unit length is too small to be included.) L and C are related as indicated above through the relation $LCv^2 = 1$; also, for a lossless line, $Z_0 = (L/C)^{1/2} \Omega$. At a frequency of 20 kHz, the skin depth in copper is 0.467 mm, with the current distributed in a circular cylindrical conductor as shown in figure 1. The distribution is governed by the relation (ref. 7)

$$\frac{I_z}{I_0} = \frac{\text{Ber}\left(\frac{r\sqrt{2}}{\delta}\right) + j\text{Bei}\left(\frac{r\sqrt{2}}{\delta}\right)}{\text{Ber}\left(\frac{r_0\sqrt{2}}{\delta}\right) + j\text{Bei}\left(\frac{r_0\sqrt{2}}{\delta}\right)} \quad (1)$$

where $\text{Ber}(x) + j\text{Bei}(x) = J_0(j^{-1/2}x)$, with $J_0(x)$ the Bessel function of the first kind and zeroth order, and $j = (-1)^{1/2}$. The other symbols are: r , radial distance; r_0 , the radius of the wire; and δ , the skin depth. In view of this distribution, calculations will be concerned mainly with wires whose diameter does not exceed 1 mm (number 18 AWG wire).

The main parameter is the inductance which should be as low as possible in order to minimize the effects of switching. Consequently, emphasis will be placed on the determination of L which will be calculated two different ways: one method will utilize the definition of inductance (flux linkage per unit current); the other method will utilize the calculation of capacitance from which the inductance will be evaluated from the relation $L = (Cv^2)^{-1} = \mu\epsilon/C = Z_0\sqrt{\mu\epsilon}$.

2.2 Inductance Calculations

In the following calculations, the permeability of all materials will be assumed to be that of free space ($\mu_0 = 4\pi \times 10^{-7}$ H/m). The inductance per unit length of a bifilar lead of radius r_a (current in each direction is assumed uniformly distributed over the cross section of the wire, see fig. 1) separated from the return lead of radius $r_{a'}$ by a distance $D_{aa'}$ is (ref. 8)

$$L_{aa'} = \frac{\mu_0}{2\pi} \left[\frac{1}{2} + \ln\left(D_{aa'}^2 / r_a r_{a'}\right) \right] = \frac{\mu_0}{4\pi} \left[1 + 4 \ln\left(D_{aa'} / r_a\right) \right] \text{ H/m} \quad (2)$$

when the return wire radius is the same as in the first wire (the case here under consideration). For an n wire system (n pairs) one can form an $n \times n$ matrix

$$\begin{bmatrix}
 L_{11} & \cdot & \cdot & \cdot & \cdot & L_{1i} & \cdot & \cdot & \cdot & \cdot & L_{1n} \\
 \cdot & \cdot & & & & \cdot & & & & & \cdot \\
 \cdot & & \cdot & & & \cdot & & & & & \cdot \\
 \cdot & & & \cdot & & \cdot & & & & & \cdot \\
 \cdot & & & & \cdot & \cdot & & & & & \cdot \\
 L_{i1} & \cdot & \cdot & \cdot & \cdot & L_{ii} & \cdot & \cdot & \cdot & \cdot & L_{in} \\
 \cdot & & & & & \cdot & \cdot & & & & \cdot \\
 \cdot & & & & & \cdot & & \cdot & & & \cdot \\
 \cdot & & & & & \cdot & & & \cdot & & \cdot \\
 L_{n1} & \cdot & \cdot & \cdot & \cdot & L_{in} & \cdot & \cdot & \cdot & \cdot & L_{nn}
 \end{bmatrix} \quad (3)$$

where $L_{ij} = L_{ji}$, and calculate the equivalent inductance of the system (refs. 9 and 10)

$$L_{eq} = \left(\sum_{i=1}^n \sum_{j=1}^n \left(\frac{1}{L_{ij}} \right) \right)^{-1} \text{ H/m} \quad (4)$$

which can be determined to any given degree of accuracy (ref. 10).

The FORTRAN program for this calculation, CRIMPD.F, which is listed in appendix A, uses a series of menus to facilitate the entry of different two-dimensional conductor geometries. The entries are the coordinates of the centers of the conductors and their respective radii, and they may be entered either in rectangular or polar coordinates, (see figs. 2 and 3 for the polar coordinates).

2.3 Check on Calculations

To check the results obtained from calculations performed according to the above discussion, two additional calculations were performed for several geometries. One check used the extension of equation (2) to multiple parallel conductors

$$L_a = \frac{\mu_0}{2\pi} \left(\frac{1}{2} + 2 \ln \frac{D_{aa'} \cdot D_{ab'} \cdot \dots \cdot D_{an'}}{r_a \cdot D_{ab} \cdot D_{ac} \cdot \dots \cdot D_{an}} \right) \text{ H/m} \quad (5)$$

with the parameters defined in figure 4. The equivalent inductance per unit length was calculated using

$$L_{eq} = \left(\sum_{i=1}^n \frac{1}{L_i} \right)^{-1} + \left(\sum_{i=1}^n \frac{1}{L_i} \right)^{-1} \text{ H/m} \quad (6)$$

Calculations for 4-, 8-, and 16-conductor arrangements agreed exactly with the other calculations.

The other check utilized the expression for capacitance between two infinitely long conductors of circular cross section (ref. 11) (radius r , distance between centers D)

$$C = \frac{\pi \epsilon}{\cosh^{-1} \left(\frac{D}{2r} \right)} = \frac{\pi \epsilon}{\ln \left(\frac{D}{2r} + \sqrt{\left(\frac{D}{2r} \right)^2 - 1} \right)} \text{ F/m} \quad (7)$$

so that the external self-inductance of one conductor is

$$L = \frac{\mu}{2\pi} \ln \left(\frac{D}{2r} + \sqrt{\left(\frac{D}{2r} \right)^2 + 1} \right) \text{ H/m} \quad (8)$$

because $LC = \mu\epsilon$. Calculations were performed using the above argument of the logarithmic function instead of using the D_{ij} 's. The results, for the ratio of the distance between conductor centers to conductor radius equal to four, are about 7 percent lower than the other calculations. This was to be expected because the internal inductance, $\mu/8\pi$, does not appear in equation (8), but its contribution is negligible for the distance-to-radius ratio of four or more, and the 7 percent discrepancy is well within bounds (ref. 10). Note that the dimensional relations of this report meet this criterion: the ratio of the distance between centers to conductor radius never is less than four. Consequently, the error-if any-should not exceed 7 percent, a value usually acceptable in practice.

3.0 CONFIGURATION DATA

3.1 Circular Cylindrical Arrangements

Calculations were performed for wire arrangements of the type shown in figures 2 and 3. For the single "ring" of wires, as in figure 2, it was found that the best arrangements (i.e., the lowest values of inductance and characteristic impedance) were for alternating current directions in adjacent wires. The values of inductance decrease with increasing number of wires. This circular configuration was not suitable, however, because of the large number of wires needed to reduce the characteristic impedance to acceptable values (on the order of an ohm). Furthermore, with an increasing number of wires, the radius of the "ring" R is increasing, and this leads to inefficient use of space.

A better configuration was of the multiring variety. Tables I and II list values of L per unit length, and of Z_0 for different number of wires (N represents the total number of wires in the line, with $N/2$ in the inner and $N/2$ in the outer ring). The angle θ is defined in figure 3 and represents the shift of the first wire in the outer ring relative to the first wire in the inner ring. As in the case of the single ring, the lowest values were obtained for alternating polarities.

One of the problems with the coaxial arrangement is that the inductances of the wires in the inner ring are lower so that more current is concentrated there relative to the outer ring. This can be compensated by reducing the radii of the wires in the inner loop.

For comparison of the different wire radii, calculations for the arrangement shown in figure 5 were made. The values for the five ring arrangement for the same wire radii (Line 1), and for different radii (Line 2), are listed in Table III. These show that in the latter case, the overall inductance is increased which means that an increase in the number of wires would be required. Clearly, this again suggests not only an inefficient use of space, but also higher L and Z_0 values than comparable rectangular arrangement (see items 1 and 2 of Table IV).

3.2 Rectangular Arrangement

To carry 100 A, #4 AWG wire is recommended (ref. 12) whose cross section is $21.15 \times 10^{-6} \text{ m}^2$. Inasmuch as the skin depth at 20 kHz is approximately 0.5 mm, the largest reasonable wire would be #18 AWG (radius, 0.512 mm; cross-sectional area, 0.8231 mm^2). The minimum number of #18 AWG wires would therefore be 26. In subsequent calculations, a larger number of wires will be used. (Note: the 26 wires do not include the return path which calls for additional 26 wires. The minimum for the line would then be 52 wires #18 AWG.)

Figures 6 to 8 show the results of 80-wire 4 by 20 rectangular arrangement which appears to have the best parameters: $L = 10.4 \text{ nH/m}$; $C = 2.5 \text{ nF/m}$; $Z_0 = 2.1 \Omega$ (the computer printed values were, respectively, 10.4196, 2.5264, 2.0611). As the method to compute these values was the "inductance" method, the numbers represent the upper bound. The wires in calculation were #18 AWG, total cross-sectional area in one direction is 32.68 mm^2 .

A calculation for 256 wires #24 AWG in an 8 by 32 arrangement, as shown in figure 9, was also made. As expected, the inductance and characteristic impedance values are lower than for the 80-wire configuration: $L = 3.2 \text{ nH/m}$, $C = 7.9 \text{ nF/m}$, $Z_0 = 0.6 \Omega$ (printout values, respectively, 3.2193, 7.9382, 0.6368); cross-sectional area, 25.1 mm^2 . Note that the variations of the self-inductance of the individual wires are greater than for the 80-wire arrangement.

Given the same size wires and the same distances among them, inductances of different size bundles are proportional to the inverse ratio of the number of conductors in the bundle. This was used to arrive at the values listed in Table V for the minimum number of wires required to pass 100-A currents. (if the self-inductances of each of the wires were the same, this relation would hold for any number of wires. Inasmuch as this is not the case (see figs. 7 to 9), the number of wires should be greater than about 20 for the approximation to be acceptable.)

Table V lists several parameters for lines composed of a minimum number of conductors that can carry the rated (100-A) current. The line lengths are 150 m each, so that the dc resistances were calculated for 300-m length to take into account the return path. The total number of wires in each line is twice that listed in the table. The corrections for the ac values were taken from

standard tables (ref. 13), and those for proximity effects from Smith (ref. 14). The proximity effects account for about additional 40 percent of resistance (see Table I and fig. 5 of ref. 14) for a distance-to-radius ratio of four (two in ref. 14 because the distance between the centers in this reference is "2c").

To adjust the value of inductance per unit length and characteristic impedance of the 52-wire #18 AWG line listed in Table V, it is only necessary to multiply by $80/52 = 1.5$, which would make $9.7 < L < 16$ nH/m, and $1.9 < Z_0 < 3.2 \Omega$. Similar adjustments can be made for the other lines.

3.3 Miscellaneous Considerations

At the rated current, about 6.5 W will be dissipated per meter of line, which would mean an increase (ref. 15) between 0.08 to 0.13 K, depending upon the type of insulation. Such temperature rise is not sufficiently large to cause concern.

The coefficient of expansion for copper is on the order of 10^{-6} m/K from 25 to 1200 K (ref. 16). At 300 K, the expansion is 16.8×10^{-6} m, which would mean a total of 2.5 mm for the entire 150-m line. This, too, is not considered significant.

For the recommended types of aircraft wire (ref. 17), Mil-W-16878, the dielectric strengths substantially exceed the specification of standing off 1 kV, which - for the recommended configuration - would be on the order $1 \text{ kV/mm} = 1 \text{ MV/m} = 25 \text{ V/mil}$. The breakdown strength of polyethylene exceeds 20 kV/mm at 20 kHz, as does that of polystyrene, Teflon, and polypropylene (ref. 18).

The conductance per unit length between the individual conductors can be calculated from the relation

$$C/G = \epsilon/\sigma \quad (9)$$

which, for the materials under consideration, will be on the order of 10^{-15} mho/m (R of the order of $10^{15} \Omega/\text{m}$), using $10^{17} \Omega\text{-m}$ for resistivity (ref. 6). Clearly the losses due to transverse currents can be neglected.

3.4 Connectors and Junction Boxes

A conventional, circular, multipin connector is shown in figure 10 as an example. Junction boxes with connecting wires, with conventional connectors of circular or rectangular shape will fulfill the specifications. The junction box shown in figures 11(a) and (b) would be more suitable, however, because the interconnecting plates substituted for wires would reduce the inductance locally. Connectors could be of the conventional, multipin variety, with soldered or brazed connections internally. Alternatively, internally the pins could be connected to blades for contact with the conductors. The specific configuration is not very critical, but it would be recommended that the connecting surfaces be gold-plated. The reason for this is to prevent increases of contact resistances as a result of fretting (ref. 19).

3.5 Miscellaneous

In addition to the configurations described above, parallel-plate arrangements of the type shown in figures 12 and 13 were analyzed. That of figure 12, in spite of the very low characteristic impedance (0.14Ω), is thought to be less suitable than the configurations recommended in the next section of the report because the thin plates will very likely buckle. Should the plates be made thicker, the line would be too heavy and too unwieldy. Also, connectors with suitable characteristics would be difficult to design.

The program for the determination of line parameters for the configuration shown in figure 13, for different values of θ , thickness, and spacing, is listed in appendix B. The values of inductances per unit length, and characteristic impedances are at least four times larger than those of the configuration shown in figure 6.

4.0 RECOMMENDATIONS

The line recommendations are made on the basis of the assumption that off-the-shelf availability, or ease for assembly-line production, are secondary to the other attributes such as low impedance, reliability, and the like. As a result, the best choices for the line are listed in Table IV. The total number of wires per 150-m line is listed, with one-half representing the return path. The direction of current alternates between neighboring lines. (The difference between Table IV and Table V is that in the latter one-half of the wires was used in a 300-m long loop for the determination of the total resistance, whereas the number of wires in the former represent two parallel sets each 150 m long.) The alternating current directions have at least two advantages: lowering the inductance of the comparable wire arrangement with adjacent currents in the same direction by at least a factor of four, and by reducing the external magnetic fields which reduces electromagnetic interference. Numbers 1 and 6 in Table IV represent the configurations of figures 6 and 9; the remainder represents the minimum number of wires required for 100-A currents.

Multipin connectors of the type generally available from manufacturers such as Litton, Amphenol, or others, would be satisfactory for the junction boxes shown in figure 11, with gold-plated contacts to prevent increases of resistance due to fretting (platinum plating would also be acceptable).

A general recommendation for any type of line used in an aircraft power distribution system is that instead of one line 150 m long there should be several 5-, 10-, or 15-m sections connected in series via junction boxes. The advantage of this would be that in case of failure of a section, it could be easily replaced—even in flight. Also, the several junction boxes at given intervals would facilitate connections to the respective loads.

PROGRAM CRIMPD.F

```

*
*
DOUBLEPRECISION A,E,C
DOUBLEPRECISION S(1:1024),O(1:1024),X(1:1024),Y(1:1024)
DOUBLEPRECISION L(0:1024),LO(0:1024),L1(0:1024),LN
DOUBLEPRECISION D(0:1024),T(1:1024),R(1:1024),B(0:1024)
DOUBLEPRECISION SA,SD,PI,SLOPEANG
INTEGER M,K,UUU,J,E,ALTPOL
INTEGER U,J,I,N,RP(1:1024)
CHARACTER Q1,POL(1:1024)*3
PARAMETER (PI=3.141592654)

*
*
100 Q1='SELECTION IS OUT OF BOUNDS. TRY AGAIN...'
CONTINUE
DO 140 I=1,64
  PRINT*
  S(I)=0.
  O(I)=0.
  X(I)=0.
  Y(I)=0.
  L(I)=0.
  LO(I)=0.
  L1(I)=0.
  D(I)=0.
  T(I)=0.
  R(I)=0.
  B(I)=0.
140 POL(I)='N'
CONTINUE
N=1
200 PRINT*('////////')
PRINT*,' Main Menu'
PRINT*,'
PRINT*,' 1. Polar coordinate input'
PRINT*,' 2. Rectangular coordinate input'
PRINT*,' 3. Data file input'
PRINT*,' 4. Run inductance calculation (Skilling method)'
PRINT*,' 5. Run capacitance calculation (Cheng method)'
PRINT*,' 6. Check individual conductors'
PRINT*,' 7. Exit to shell'
PRINT*,' 8. Enter new configuration (reset index counter)'
PRINT*,'(//)'

*
PRINT*,'Choose from 1 thru 8...'
READ*,U
IF(U.EQ. 7)GOTO 7000
IF(U.EQ. 6)GOTO 6000
IF(U.EQ. 5)GOTO 250
IF(U.EQ. 4)GOTO 4000
IF(U.EQ. 3)GOTO 250
IF(U.EQ. 2)GOTO 2000
IF(U.EQ. 1)GOTO 1000
IF(U.EQ. 8)GOTO 100
PRINT*,Q1
GOTO 200
250 PRINT*,'ROUTINE NOT OPERATIVE,CHOOSE ANOTHER MODE...'
GOTO 200

*
*
1000 Polar coordinate input
PRINT*,' Polar coordinate input'
PRINT*,' 1. Automatic ring program'
PRINT*,' 2. Individual input'
PRINT*,' 3. Exit to main menu'

*
PRINT*,'Choose one...'
READ*,U
IF(U.EQ. 3)GOTO 200
IF(U.EQ. 2)GOTO 1500
IF(U.EQ. 1)GOTO 1100
PRINT*,Q1
GOTO 1000

*
*
1100 Auto polar ring
PRINT*,'AUTO POLAR RING'
PRINT*,'Input number of conductors in this ring...'
READ*,M
SA=2.0*PI/REAL(M)
SD=SA*180.0/PI

```

```

PRINT*, 'input coordinates, radius and polarity of 1st conductor'
PRINT*, 'in this ring (r(mm),theta(degrees),radius(mm),+ or -)'
1110 READ(5,1110) S(N),T(N),R(N),POL(N)
      FORMAT(F8.4,F8.4,F8.4,A1)
      O(N)=T(N)*PI/180.0
      S(N)=S(N)/1000.0
      R(N)=R(N)/1000.0
      X(N)=S(N)*COS(O(N))
      Y(N)=S(N)*SIN(O(N))
      RP(N)=0
1120 PRINT*(///A), 'Choose polarity of wires...'
      PRINT*, '1. Alternating'
      PRINT*, '2. All the same as 1st'
      PRINT*, '3. Individually selected'
      PRINT*, '4. Exit to last menu'
1160 READ*,U
      IF(U .EQ. 1)GOTO 1200
      IF(U .EQ. 2)GOTO 1220
      IF(U .EQ. 3)GOTO 1180
      IF(U .EQ. 4)GOTO 1000
      PRINT*,01
      GOTO 1120
*
1180 UUU=1
      GOTO 1260
1200 UU=0
      GOTO 1260
1220 UU=1
1260 DO 1340 I=N+1,N+M-1
      RP(I)=0
      S(I)=S(N)
      O(I)=O(I-1) + SA
      T(I)=T(I-1) + SD
      X(I)=S(I)*COS(O(I))
      Y(I)=S(I)*SIN(O(I))
      R(I)=R(N)
1280 IF(UUU .NE. 1)GOTO 1300
      PRINT*(//,T2,A,I3,A,F8.5,2X,F8.4), 'Conductor',I , 'with coords.',S(I)*1000.0,T(I)
      PRINT*, 'Input polarity (+ or -)...'
      READ*(A),POL(I)
1300 IF(U .EQ. 2)GOTO 1320
      IF(POL(I-1) .EQ. '+')POL(I)='-'
      IF(POL(I-1) .EQ. '-')POL(I)='+'
      GOTO 1340
1320 POL(I)=POL(I-1)
1340 CONTINUE
*
      N=N+M
      GOTO 200
*
* Individual polar input
1500 PRINT*, 'Individual Polar Inputs'
      PRINT*, 'How many conductors in this series?'
      READ*,K
      DO 1560 I=N,N+K-1
      PRINT*, 'Input r(mm),theta(degrees),radius of conductor(mm),polarity(+ or -)...'
      READ(5,1110) S(I),T(I),R(I),POL(I)
      RP(I)=0
      R(I)=R(I)/1000.0
      S(I)=S(I)/1000.0
      O(I)=T(I)*PI/180.0
      X(I)=S(I)*COS(O(I))
      Y(I)=S(I)*SIN(O(I))
1560 CONTINUE
      N=N+K
      GOTO 200
*
*
* rectangular coordinate input
2000 CONTINUE
      PRINT*, 'RECTANGULAR COORDINATE INPUT'
2100 PRINT*, 'Choose one...'
      PRINT*, '1. Individual input'
      PRINT*, '2. Line input (equally spaced wires)'
      PRINT*, '3. Return to main menu'
      READ*,U
      IF(U .EQ. 1)GOTO 2120
      IF(U .EQ. 2)GOTO 2200
      IF(U .EQ. 3)GOTO 200

```

```

2120 PRINT*, 'Individual Rectangular Inputs'
PRINT*, 'How many conductors in this series....'
READ*, K
DO 2150 I=N, N+K-1
  PRINT*
  PRINT*, 'Input coordinates, radius & polarity of cond.', I, '.'
  PRINT*, '(X(mm), Y(mm), r(mm), + or -)'
  READ(5, 1110) X(I), Y(I), R(I), POL(I)
  RP(I)=1
  X(I)=X(I)/1000.0
  Y(I)=Y(I)/1000.0
  R(I)=R(I)/1000.0
  S(I)=SQRT(X(I)**2.0+Y(I)**2.0)
  IF(S(I) .EQ. 0.0) GOTO 2140
  T(I)=180.0/PI*ACOS(X(I)/S(I))
  GOTO 2150
2140 T(I)=0.0
2150 CONTINUE
N=N+K
GOTO 200

*
* AUTO LINE
2200 CONTINUE
PRINT*, 'AUTO LINE INPUT'
PRINT*, 'Input coordinates, radius & polarity of 1st conductor....'
PRINT*, '(X(mm), Y(mm), r(mm), + or -)....'
READ(5, 1110) X(N), Y(N), R(N), POL(N)
X(N)=X(N)/1000.0
Y(N)=Y(N)/1000.0
R(N)=R(N)/1000.0
S(N)=SQRT(X(N)**2.0 + Y(N)**2.0)
IF(S(N) .EQ. 0.0) GOTO 2210
T(N)=180.0/PI*ACOS(X(N)/S(N))
GOTO 2230
2210 T(N)=0.0
2230 CONTINUE
RP(N)=1
PRINT*
PRINT*, 'Input number of conductors on this line...'
READ*, M
PRINT*, 'Input distance between centers of conds on this line (SPACING)....'
READ*, SPACING
SPACING=SPACING/1000.0
PRINT*, 'Input slope angle of the line (positive x-axis=0 degrees)'
READ*, SLOPEANG
SLOPEANG=SLOPEANG*PI/180.0
DO 2300 I=N+1, N+M-1
  X(I)=X(I-1) + SPACING*COS(SLOPEANG)
  Y(I)=Y(I-1) + SPACING*SIN(SLOPEANG)
  R(I)=R(I-1)
  S(I)=SQRT(X(I)**2+Y(I)**2)
  T(I)=ACOS(X(I)/S(I))*180.0/PI
  RP(I)=1
2300 CONTINUE
2320 CONTINUE
PRINT* (///A), 'Choose polarity of wires....'
PRINT*, '1. Alternating'
PRINT*, '2. All the same as the 1st'
PRINT*, '3. Individually selected'
PRINT*, '4. Return to last menu'
READ*, U
IF(U .EQ. 1) GOTO 2340
IF(U .EQ. 2) GOTO 2380
IF(U .EQ. 3) GOTO 2420
IF(U .EQ. 4) GOTO 2000
PRINT*, 'Q1'
GOTO 2320
2340 CONTINUE
IF(POL(N) .EQ. '+') THEN
  ALTPOL=1
ELSEIF(POL(N) .EQ. '-') THEN
  ALTPOL=-1
ENDIF
DO 2360 I=N+1, N+M-1
  IF(ALTPOL .EQ. 1) THEN
    POL(I)='+'
  ELSEIF(ALTPOL .EQ. -1) THEN
    POL(I)='-'
  ENDIF
  ALTPOL=-ALTPOL

```

```

2360      CONTINUE
        N=N+M
        GOTO 200
*
2380      CONTINUE
        DO 2400 I=N+1,N+M-1
          POL(I)=POL(N)
2400      CONTINUE
        N=N+M
        GOTO 200
*
2420      CONTINUE
        DO 2440 I=N+1,N+M-1
          PRINT*('T2,A,I3,A,F8.5,2X,F8.4'),'conductor',I,'with coords. x(mm)='X(I),'y(mm)='Y(I)
          PRINT*,'input polarity (+ or -)...'
          READ*,POL(I)
2440      CONTINUE
        N=N+M
        GOTO 200
*
*
*
*
3000      continue
*
*
*
4000      D(0)=1.0
        PRINT*,'input value of dielectric constant...'
        READ*,E
4050      print*
4140      DO 4320 I=1,N-1
        IF(POL(I).EQ.'-')GOTO 4220
        DO 4200 J=1,N-1
          IF(J.EQ.I)GOTO 4160
          D(J)=SQRT((X(J)-X(I))**2+(Y(J)-Y(I))**2)
          IF(POL(J).EQ.'-')GOTO 4180
          D(J)=1.0/D(J)
          GOTO 4180
        D(J)=1.0
        D(J)=D(J)*D(J-1)
4160
4180      CONTINUE
4200      GOTO 4300
*
4220      D(0)=1.0
        DO 4280 J=1,N-1
          IF(J.EQ.I)GOTO 4240
          D(J)=SQRT((X(I)-X(J))**2+(Y(I)-Y(J))**2)
          IF(POL(J).EQ.'+')GOTO 4260
          D(J)=1.0/D(J)
          GOTO 4260
        D(J)=1.0
        D(J)=D(J)*D(J-1)
4240
4260      CONTINUE
4280      L(I)=(0.5+2.0*LOG(D(N-1)/R(I)))*100.0
4300      CONTINUE
4320
*
*
        LO(0)=0.0
        LI(0)=0.0
        DO 4440 I=1,N-1
          IF(POL(I).EQ.'-')GOTO 4400
          LI(I)=1.0/L(I)
          LO(I)=0.0
          GOTO 4420
        LI(I)=0.0
        LO(I)=1.0/L(I)
        LI(I)=LI(I)+LI(I-1)
        LO(I)=LO(I)+LO(I-1)
4400
4420      CONTINUE
4440
*
        B(0)=0.0
        DO 4460 I=1,N-1
          B(I)=R(I)*1000.0
          A=(B(I))**2+(B(I-1))**2
          B(I)=SQRT(A)
4460      CONTINUE
        A=A*PI/2.0
        IF(ABS(LO(N-1)).LE.0.0000001)GOTO 4480
        LN=1.0/LI(N-1)+1.0/LO(N-1)

```

```

4470 goto 4490
4480 LN=1.0/L1(N-1)
4490 CONTINUE
C=E*100.0/9.0/LN
PRINT*(T2,A,F10.4,A),',',INDUCTANCE OF CIRCUIT IS L=',LN,'nH/m'
PRINT*(T2,A,F10.4,A),',',CAPACITANCE IS C=',C,'nF/m'
PRINT*(T2,A,F10.4,A),',',CHAR. IMPED. IS Z=',SQRT(LN/C),'ohms'
PRINT*(T2,A,T51,F10.4,T62,A//),',',TOTAL CROSS-SECT. AREA IN ONE DIRECTION IS A=',A,'sq. mm'
* PRINT*('/')
*
PRINT*(2X,A,T10,A,T20,A,T30,A,T37,A,T50,A,T60,A,T72,A),',',cond',',x(mm)',',y(mm)',',r(mm)',',theta(deg)',',polarity',',radius',',L'
DO 4640 I=1,N-1
IF(RP(I).EQ.1)GOTO 4600
PRINT*(2X,I3,T25,F10.4,T36,F10.4,T53,A,T56,F10.4,T67,F10.4),',',I,S(I)*1000.0,T(I),POL(I),R(I)*1000.0,L(I)
GOTO 4640
*
4600 continue
PRINT*(2X,I3,T7,F10.4,T18,F10.4,T53,A,T56,F10.4,T67,F10.4),',',I,X(I)*1000.0,Y(I)*1000.0,POL(I),R(I)*1000.0,L(I)
4640 CONTINUE
4700 PRINT*
goto 200
*
*
*
*
5000 continue
*
*
*
*
6000 PRINT*,',',Check individual conductors'
PRINT*,',',Input number of 1st conductor to be checked...'
READ*,J
PRINT*,',',Input number of last conductor to be checked...'
READ*,JE
PRINT*(2X,A,T9,A,T18,A,T33,A,T43,A,T50,A,T60,A),',',cond',',r(mm)',',theta(deg)',',x(mm)',',y(mm)',',polarity',',radius'
DO 6200 I=J,JE
PRINT*(2X,I3,T7,F8.4,T21,F9.3,T31,F8.4,T41,F8.4,T54,A,T58,F8.4),',',I,S(I)*1000.0,T(I),X(I)*1000.0,Y(I)*1000.0,POL(I),R(I)*1000
6200 CONTINUE
6300 PRINT*,',',Check another conductor? (1=yes,0=no)...'
READ*,U
IF(U.EQ.1)GOTO 6000
IF(U.EQ.0)GOTO 200
PRINT*,Q1
GOTO 6300
*
*
7000 PRINT*,',',Are you sure you want to exit program?'
PRINT*,',',1=YES'
PRINT*,',',2=NO'
READ*,U
IF(U.EQ.2)GOTO 200
IF(U.EQ.1)GOTO 7500
PRINT*,Q1
GOTO 7000
7500 PRINT*
END

```



```

PROGRAM LAPLAC
*specifications-----
INTEGER NMIN,NMAX,MMIN,MMAX
INTEGER P(0:64,0:64),L
INTEGER N,M,N1,N2,N3,N4,M1,M2,NS,MS
INTEGER LMAX,LS,OUT,IN,ID,JD,LT
INTEGER I,J,K,KD,KQ,KT,KMAX,JSL,MM2,MM3,M2SL,RPN1,RPM1
REAL SL,ERLIM,ACAP,DCAP,RPA,RPB,RPC
REAL ERMAL,LAMBDA
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
CHARACTER PS(0:18)*1
COMMON F,P,C,L,H,RP1,RP2
COMMON/RELAX/LAMBDA,ERMAL,I,J
COMMON/CONTOUR/NMIN,NMAX,MMIN,MMAX
*initializations-----
DATA N,M,NMIN,NMAX,MMIN,MMAX/32,64,0,20,0,48/
DATA ERLIM,KMAX/1E-4,100/
DATA N1,N2,N3,N4,M1,M2,NS,MS/4,12,16,4,16,32,6,18/
DATA (PS(I),I=0,18)/
:
:
:
DATA LAMBDA,LMAX,H/1.4,4,0.125/
DATA RP1,RP2,RPN1,RPM1,KD,KT/1,1,16,32,0,0/
*function statements-----
IRND(F1)=NINT(F1*1E3)
*data inputs-----
PRINT '(A)', 'OUTPUT TYPE (0=ALL, 1=FINAL, 2=DATA FILE)?'
READ*,OUT
PRINT '(A)', 'INPUT TYPE (0=INTERNAL,1=EXTERNAL,2=DATA FILE)'
READ*,IN
IF(IN.EQ.2)THEN
  READ '(3I3,2F6.3)',N,M,L,H,SL
  DO 2 JD=0,M
    DO 1 ID=0,N
      READ '(2I3,E15.7,I3)',I,J,F(ID,JD),P(ID,JD)
      CONTINUE
    CONTINUE
  CALL CNTOUR
  GOTO 999
ENDIF
IF(IN.LT.1)THEN
  PRINT '(A)', 'INPUT SLOPE( 0,0.5,1,2,3=NO FLAP ):'
  READ*,SL
ENDIF
PRINT '(/T2,A,F6.3,A//,10A5,2A8)',
:
:
:
'BOUNDARY DIMENSIONS( 1='H','mm ):',
:
'N','M','N1','N2','N3','N4','M1','M2','NS','MS','SLOPE','LAMBDA'
IF(IN.LT.1)GOTO 4
READ*,N,M,N1,N2,N3,N4,M1,M2,NS,MS,SL,LAMBDA
4
PRINT '(10I5,2F8.3//)',N,M,N1,N2,N3,N4,M1,M2,NS,MS,SL,LAMBDA
PRINT '(T3,A//,4A6)',
:
'INPUT CONTOUR LIMITS','NMIN','NMAX','MMIN','MMAX'
IF(IN.LT.1)GOTO 5
READ*,NMIN,NMAX,MMIN,MMAX
5
PRINT '(4I6//)',NMIN,NMAX,MMIN,MMAX

```

```

*boundary conditions-----
PRINT'(A)', 'HOMOGENEOUS DIELECTRIC CONSTANT(YES=GE(1),NO=LE(-1))'
READ*,RP1
IF(RP1 .GT. 0)THEN
  KD=0
  RP2=RP1
  RP1=1.0
ELSE
  RP2=ABS(RP1)
  RP1=1.0
  KD=0
PRINT'(A)', 'DIELECTRIC CONFIGURATION(1=INSIDE,2=OUTSIDE)'
READ*,KD
IF(KD .EQ. 1)THEN
  KT=0
  PRINT'(A)', 'DISTANCE FROM CENTER=?'
  READ*,KT
  RPM1=M1+KT
  RPN1=N3
ELSE
  PRINT'(A)', 'OUTSIDE LAYER THICKNESS=?'
  READ*,KT
  RPN1=N3+KT
  RPM1=M2+KT
ENDIF
ENDIF
RPA=2*RP1
RPB=2*RP2
RPC=RP1+RP2
*point type array setup-----
*homogeneous interior point-----
DO 7 J=1,5
  C(5,J)=RPA
7 CONTINUE
DO 8 J=1,5
  C(6,J)=RPB
8 CONTINUE
*dielectric in two adjacent quadrants -----
C(7,1)=RPC
C(7,2)=RPC
C(7,3)=RPA
C(7,4)=RPB
C(7,5)=RPC*2
C(8,1)=RPA
C(8,2)=RPB
C(8,3)=RPC
C(8,4)=RPC
C(8,5)=RPC*2
C(9,1)=RPC
C(9,2)=RPC
C(9,3)=RPB
C(9,4)=RPA
C(9,5)=2*RPC
C(10,1)=RPA
C(10,2)=RPB
C(10,3)=RPC
C(10,4)=RPC

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```

      C(10,5)=2*RPC
*dielectric in one quadrant-----
      C(11,1)=RPA
      C(11,2)=RPC
      C(11,3)=RPA
      C(11,4)=RPC
      C(11,5)=RPC+RPA
      C(12,1)=RPA
      C(12,2)=RPC
      C(12,3)=RPC
      C(12,4)=RPA
      C(12,5)=RPC+RPA
      C(13,1)=RPA
      C(13,2)=RPC
      C(13,3)=RPA
      C(13,4)=RPC
      C(13,5)=RPC+RPA
      C(14,1)=RPC
      C(14,2)=RPA
      C(14,3)=RPA
      C(14,4)=RPC
      C(14,5)=RPC+RPA
*dielectric in three quadrants-----
      C(15,1)=RPC
      C(15,2)=RPB
      C(15,3)=RPC
      C(15,4)=RPB
      C(15,5)=RPC+RPB
      C(16,1)=RPC
      C(16,2)=RPB
      C(16,3)=RPB
      C(16,4)=RPC
      C(16,5)=RPC+RPB
      C(17,1)=RPC
      C(17,2)=RPB
      C(17,3)=RPC
      C(17,4)=RPB
      C(17,5)=RPC+RPB
      C(18,1)=RPB
      C(18,2)=RPC
      C(18,3)=RPC
      C(18,4)=RPB
      C(18,5)=RPC+RPB
*initial point type-----
      DO 10 I=0,N
        DO 9 J=0,M
          F(I,J)=0.0
          DC(I,J)=RP1
          P(I,J)=5
        9 CONTINUE
      10
*defined boundaries-----
      DO 600 LS=2,0,-1
        L=(2**LS)
        KQ=KMAX/REAL(L)
*upper boundary (x,y=m)*-----
      DO 15 I=0,N,L
        P(I,M)=2

```

```

15      CONTINUE
*right boundary (x=n,y)*-----
      DO 20 J=0,M,L
        P(N,J)=2
20      CONTINUE
*lower dielectric boundary (x,y=0)*--
      DO 30 I=(N1+L),(N2-L),L
        P(I,0)=3
30      CONTINUE
      DO 35 I=(N3+L),N,L
        P(I,0)=3
35      CONTINUE
*left dielectric boundary (x=0,y)*---
      DO 40 J=(M1+L),M,L
        P(0,J)=4
40      CONTINUE
*defined conductors-----
*center conductor (x,y)*-----
      DO 55 I=0,N1,L
        DO 50 J=0,M1,L
          F(I,J)=1.0
          P(I,J)=1
50      CONTINUE
55      CONTINUE
*outer conductor (x,y)*-----
      DO 65 I=N2,N3,L
        DO 60 J=0,M2,L
          P(I,J)=2
60      CONTINUE
65      CONTINUE
16 *outer conductor edge(x,y)*-----
      IF(SL .GT. 2) GOTO 80
      MM2=M2-LMAX
      MM3=M2+5*LMAX
      DO 75 J=MM2,MM3,L
        DO 70 I=N3,N4,-L
          JSL=NINT(SL*(N2-I)/L)*L
          M2SL=M2+JSL
          IF(((M2SL-(N3-N2+L)) .LT. J .AND. J .LE. M2SL) .OR.
            : (N2 .LE. I .AND. J .LT. M2SL)) THEN
            F(I,J)=0.0
            P(I,J)=2
          ELSE
            P(I,J)=5
          ENDIF
70      CONTINUE
75      CONTINUE
*second dielectric fill-----
80      IF(KD .GT. 0) THEN
        DO 140 J=1,(RPM1-L)
          DO 120 I=1,(RPN1-L)
            IF(P(I,J) .GT. 4) THEN
              P(I,J)=6
            ENDIF
120          CONTINUE
            IF(KD .EQ. 2) THEN
              P(RPN1,J)=8
            ENDIF
140          CONTINUE

```

```

DO 160 I=1,(RPN1-1)
  IF(P(I,RPM1) .GT. 4) THEN
    P(I,RPM1)=7
  ENDIF
160 CONTINUE
  IF(KD .EQ. 2) THEN
    P(RPN1,RPM1)=11
  ENDIF
ENDIF
*air pocket location-----
IF(L .GT. 1) GOTO 180
170 PRINT(A), 'INPUT AIR POCKET LOCATION(I,J),(-1,X)=NONE]'
READ*,I,J
LT=1
IF(I .GT. 0) THEN
  P(I,J)=5
  P(I-LT,J)=5
  P(I+LT,J)=5
  P(I,J-LT)=5
  P(I,J+LT)=5
  P(I-2*LT,J)=7
  P(I,J-2*LT)=8
  P(I+2*LT,J)=9
  P(I,J+2*LT)=10
  P(I-LT,J-L)=11
  P(I+LT,J-L)=12
  P(I+LT,J+L)=13
  P(I-LT,J+L)=14
  P(I-2*LT,J-L)=15
  P(I-LT,J-2*L)=15
  P(I+LT,J-2*L)=16
  P(I+2*LT,J-L)=16
  P(I+2*LT,J+L)=17
  P(I+LT,J+2*L)=17
  P(I-LT,J+2*L)=18
  P(I-2*LT,J+L)=18
  GOTO 170
ENDIF
*point type printout-----
180 IF(OUT .EQ. 1 .AND. L .GT. 1) GOTO 200
  IF(OUT .GT. 1) GOTO 200
  PRINT(' /T2,A//,T5,A,I2,/) ',
    : 'BOUNDARY CONDITIONS', 'MESH SIZE =',L
  PRINT(' (T5,A//,T5,A//) ', '+:V=1000, *:V=0', '|:dV/dy=0, -:dV/dx=0'
  DO 190 J=M,0,-L
    PRINT(' (T6,33A) ',(PS(P(I,J))),I=0,N,L)
190 CONTINUE
  PRINT(' (//) '
200 CONTINUE
*lambda loop-----
*iterate solution-----
DO 230 K=1,KQ
  IF(K .EQ. 1) THEN
    ERMAX=1
  ELSE
    ERMAX=0
  ENDIF

```

```

      DO 220 J=0,M,L
        DO 210 I=0,N,L
          CALL PTCALC
210      CONTINUE
220      CONTINUE
      IF(ERMAX .LE. ERLIM) GOTO 240
230      CONTINUE
      K=0
240      CONTINUE
250      IF(L .LE. 1 .OR. OUT .LT. 1) THEN
        CALL CAPCT(NS,MS,ACAP,DCAP)
      ENDIF
*output analysis-----
300      IF(OUT .EQ. 2) GOTO 500
      IF(L .GT. 1 .AND. OUT .GT. 0) GOTO 600
      IF(K .EQ. 0) THEN
        PRINT'(T2,A,I4,A,/)','
      :   'SOLUTION HAS NOT CONVERGED IN ',KQ,' ITERATIONS'
      ELSE
        PRINT'(T2,A,I4,A,/)','
      :   'SOLUTION CONVERGED AFTER ',K,' ITERATIONS'
      ENDIF
320      PRINT'(T2,A,F9.6,/)','
      :   'WITH A MAXIMUM ABSOLUTE ERROR OF',ERMAX
      PRINT'(T2,A,I3,A,/,T2,A,F6.3,/)','
      :   'MESH SIZE=',L,' * STEP SIZE',LAMBDA ='LAMBDA
      PRINT'(T2,A,F10.6,A,/)','CORNER CAPACITANCE (AIR) =',ACAP,'pF/m'
      PRINT'(//////////)','
*solution array printout-----
      IF(LS .LT. 1) THEN
        PRINT'(T2,A,/)','SOLUTION AT n*m POINTS, (x=horiz, y=vert):'
        DO 400 J=M,0,-L
          PRINT'(T2,33(I4))',(IRND(F(I,J)),I=0,N,L)
400      CONTINUE
      PRINT'(///,T2,A,/,T2,A,/)','
      :   'CONSTANT VOLTAGE CONTOUR PLOT','+:V=1000 *:V=0 .:V<10'
      CALL CNTOUR
      ENDIF
      GOTO 600
*data file output-----
500      IF(L .EQ. 1) THEN
        PRINT'(3I3,2F6.3)',N,M,L,H,SL
        DO 520 J=0,M
          DO 510 I=0,N
            PRINT'(2I3,E15.7,I3)',I,J,F(I,J),P(I,J)
510          CONTINUE
520          CONTINUE
        PRINT'(I3)',-1
        GOTO 999
      ENDIF
*termination-----
600      CONTINUE
      PRINT'(//A/,A,////////)', 'CHANGE PARAMETERS? (-1 TO END, 1=FLAP SLOPE,',
      :   '2=LAMBDA, 3=BOUNDARY CONDITIONS)'
      READ'(I3)',I
      IF(I .LT. 0) GOTO 999
      GOTO(620,630,640),I

```

```

620 READ*,SL
    GOTO 3
630 READ*,LAMBDA
    GOTO 3
640 IN=1
    GOTO 3
999 END
*****
SUBROUTINE PTCALC
*specifications-----
INTEGER I,J,PK
INTEGER P(0:64,0:64),L
REAL F1,F2,F3,F4,F5,F6,F7,F8
REAL C1,C2,C3,C4,C5
REAL PAST,TEMP,ER,FINT,FNORM,FDIEL
REAL ERMAX,LAMBDA
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
COMMON F,P,C,L,H,RP1,RP2
COMMON/RELAX/LAMBDA,ERMAX,I,J
*function statements-----
FINT(F1,F2,F3,F4,F5,F6,F7,F8)=(4*(F1+F2+F3+F4)+(F5+F6+F7+F8))*0.05
FNORM(F1,F2)=(4*F2-F1)/3
FDIEL(F1,F2,F3,F4,C1,C2,C3,C4,C5)=(C1*F1+C2*F2+C3*F3+C4*F4)/(2*C5)
*relaxation-----
PK=P(I,J)
GOTO (195,195,120,140,180,180,160,160,160,160),PK
120 TEMP=FNORM(F(I,(2*L)),F(I,L))
    GOTO 190
140 TEMP=FNORM(F((2*L),J),F(L,J))
    GOTO 190
160 TEMP=FDIEL(F(I+L,J),F(I-L,J),F(I,J+L),F(I,J-L),
: C(PK,1),C(PK,2),C(PK,3),C(PK,4),C(PK,5))
    GOTO 190
180 TEMP=FINT(F(I+L,J),F(I-L,J),F(I,J+L),F(I,J-L),
: F(I+L,J+L),F(I+L,J-L),F(I-L,J+L),F(I-L,J-L))
190 PAST=F(I,J)
    F(I,J)=PAST+LAMBDA*(TEMP-PAST)
    ER=ABS(PAST-F(I,J))
    ERMAX=MAX(ERMAX,ER)
195 RETURN
    END
*****
SUBROUTINE CAPCT(NS,MS,ACAP,DCAP)
*specifications-----
INTEGER NS,MS
INTEGER P(0:64,0:64),L
REAL ENORM,PERMFS,ACAP,DCAP
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
COMMON F,P,C,L,H,RP1,RP2
PARAMETER (PERMFS=8.85419)
*surface integration-----
ENORM=0.0
ENORM=(F(NS+L,0)-F(NS-L,0)+F(NS+L,MS)-F(NS-L,MS))*0.5
ENORM=ENORM+(F(0,MS+L)-F(0,MS-L)+F(NS,MS+L)-F(NS,MS-L))*0.5
DO 10 J=L,(MS-L),L
    ENORM=ENORM+F(NS+L,J)-F(NS-L,J)
10 CONTINUE

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```

DO 20 I=L,(NS-L),L
  ENORM=ENORM+F(I,MS+L)-F(I,MS-L)
20 CONTINUE
  ACAP=ABS((5E-4*PERMFS*(NS+MS)*ENORM)/H)
  DCAP=RP2*ACAP
  RETURN
END
*****
SUBROUTINE CNTOUR
*specifications-----
  INTEGER IR,IC,NCOL,MROW,MARKX,MARKY
  INTEGER I,J,NO,MO,DN,DM,PD
  INTEGER NMIN,NMAX,MMIN,MMAX
  INTEGER P(0:64,0:64),L
  REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
  CHARACTER DARY(0:132,0:260)*1,CS(0:16)*1
  COMMON F,P,C,L,H,RP1,RP2
  COMMON/CONTOR/NMIN,NMAX,MMIN,MMAX
  COMMON/CHRSET/DARY,CS
  COMMON/INTSET/I,J,NO,MO,DN,DM,PD
*initializations-----
  DATA NCOL,MROW,MARKX,MARKY/128,256,5,4/
  DATA DN,DM/5,4/
  DATA (CS(I),I=0,16)/
  : '0','1','2','3','4','5','6','7','8','9','0',
  : '+','*','!','-','.';
*character array clear-----
DO 20 IR=0,MROW
  DO 10 IC=0,NCOL
    DARY(IC,IR)=CS(15)
  10 CONTINUE
20 CONTINUE
*character array fill-----
DO 40 J=MMIN,MMAX
  MO=(J-MMIN)*DM
  DO 30 I=NMIN,NMAX
    NO=(I-NMIN)*DN
    IF(P(I,J).LT. 3)THEN
      PD=(-P(I,J))
      CALL CHRFIL
    ELSE
      IF(I.GT. NMIN)THEN
        IF(P(I-L,J).LT. 3)THEN
          PD=1
          CALL CHRFIL
        ENDIF
      ENDIF
      IF(J.GT. MMIN)THEN
        IF(P(I,J-L).LT. 3)THEN
          PD=2
          CALL CHRFIL
        ENDIF
      ENDIF
      PD=0
      CALL CHRFIL
    ENDIF
  30 CONTINUE
40 CONTINUE

```



```

40      CONTINUE
*printing character array-----
DO 50 IR=((MMAX-MMIN)*DM),0,-L
    PRINT*(132A1)',(DARY(IC,IR),IC=0,((NMAX-NMIN)*DN))
50      CONTINUE
    RETURN
    END
*****
SUBROUTINE CHR FIL
*specifications-----
INTEGER CF,I,I,LJ
INTEGER N,M
INTEGER I,J,NO,MO,DN,DM,PD
INTEGER P(0:64,0:64),L
REAL FS,RRMIN,RMIN,RMAX,NX,MY,MPN
REAL F(0:64,0:64),C(0:18,1:5),H,RP1,RP2
CHARACTER DARY(0:132,0:260)*1,CS(0:16)*1
COMMON F,P,C,L,H,RP1,RP2
COMMON/CHRSET/DARY,CS
COMMON/INTSET/I,J,NO,MO,DN,DM,PD
*initializations-----
DATA RRMIN,RMIN,RMAX/0.01,0.05,0.95/
*character array DN*DM segment fill-----
LI=L
LJ=L
IF(PD .LT. 0) THEN
    CF=(10-PD)
    DARY(NO,MO)=CS(CF)
    GOTO 99
ELSE
    IF(PD .EQ. 1) THEN
        LI=-L
    ELSE
        IF(PD .EQ. 2) THEN
            LJ=-L
        ENDIF
    ENDIF
ENDIF
DO 30 M=0,(DM-1)
    DO 20 N=0,(DN-1)
        IF(PD .GE. 0) THEN
            IF((N+M) .LT. 1) THEN
                FS=F(I,J)
            ELSE
                NX=N/REAL(DN)
                MY=M/REAL(DM)
                MPN=NX*MY
                FS=F(I,J)*(1.0+MPN-NX-MY)+F(I+LI,J)*(NX-MPN)+
                F(I,J+LJ)*(MY-MPN)+F(I+LI,J+LJ)*MPN
            ENDIF
            IF(FS .LT. RRMIN) THEN
                CF=16
            ELSE
                IF(FS .LT. RMIN .OR. FS .GT. RMAX) THEN
                    CF=10
                ELSE

```

```

                IF(FS .GE. 0.999) THEN
                  CF=INT(FS*10)
                ELSE
                  CF=NINT(FS*10)
                ENDIF
            ENDIF
        ENDIF
    ENDIF
    DARY(NO+N*LI,MO+M*LJ)=CS(CF)
10  CONTINUE
20  CONTINUE
30  RETURN
99  END

```

*=====

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TABLE I. - CHARACTERISTIC IMPEDANCE AND INDUCTANCE OF
DOUBLE LAYER MULTICONDUCTOR LINES ("INDUCTANCE" METHOD)

Number of wires	R ₁ , mm	R ₂ , mm	R ₁ , mm	R ₂ , mm	θ, deg	Z, Ω	L, nH/m
8	25	50	0.5	0.5	0	78.5	396.8
8	25	50	.5	.5	45	88.7	448.2
16	25	50	0.5	0.5	0	36.2	182.9
16	25	50	.5	.5	25.5	37.4	189.2
32	25	50	0.5	0.5	0	15.2	76.9
64	25	50	.5	.5	0	5.9	29.7
8	10	25	0.5	0.5	0	65.6	331.9
16	10	25	.5	.5	0	28.6	144.4
16	25	50	0.5	1.0	0	33.1	167.2
32	25	50	.5	2.0	0	11.7	59.3
32	25	50	1.0	2.0	0	10.3	51.9
64	25	50	.5	2.0	0	4.1	20.8
16	10	25	0.5	4.0	0	17.2	87.2
32	10	25	1.0	4.0	0	4.3	21.8

TABLE II. - Z₀ AND L OF DOUBLE RING MULTICONDUCTOR
LINES ("CAPACITANCE" METHOD)

R ₁ , mm	R ₂ , mm	θ, deg	r, mm	Total number of wires in line, N	Z ₀ , Ω	L, nH/m
25	50	0	0.5	8	73.5	371.5
25	↓	45	↓	8	83.7	423.0
25	↓	0	↓	16	33.7	170.0
25	↓	22.5	↓	16	34.9	176.5
25	50	0	0.5	32	13.9	70.5
25	↓	↓	1	32	10.4	52.6
25	↓	↓	2	32	6.6	33.3
25	↓	↓	4	32	0.22	1.09
25	50	0	1	64	3.3	16.8
25	50	↓	2	64	.17	.88
10	25	↓	1	16	18.7	94.4
10	25	↓	.5	32	9.6	48.6
10	25	0	1	32	5.4	27.6
10	25	0	.5	64	3.0	15.1

TABLE III. - 64-WIRE, 5-RING TRANSMISSION LINES

Ring	Number in ring	r, mm	Coordinates (1st)		Polarity (1st)	Ring polarity
			R, mm	r, deg		

Line 1 (all radii the same #18 AWG)

1	8	0.51	2.6393	0	+	Alt.
2	8	↓	4.6593	↓	-	↓
3	16		6.6793		+	
4	16		8.6993		-	
5	16	↓	10.7193	↓	+	↓

Line 2 (five different wire sizes)

1	8	0.3	2.6393	0	+	Alt.
2	8	.51	4.6593	0	-	Alt.
3a	4	.27	6.6793	0	+	Same
3b	8	.45	↓	22.5	-	Same
3c	4	.51	↓	45	+	Same
4a	4	.45	8.6993	0	-	Same
4b	8	.35	↓	22.5	+	Same
4c	4	.3	↓	45	-	Same
5	16	.51	10.7193	0	+	Alt.

DATA OUTPUT		
	Line 1	Line 2
L, nH/m	15.33	18.70
C, nF/m	1.67	1.37
Z, Ω	3.03	3.70
A, mm ²	26.15	18.95

TABLE IV. - RECOMMENDED WIRE ARRANGEMENTS FOR POWER LINE

Number	Wire size (#AWG)	Total number of wires	Ranges of values inductance, nH/m		Characteristic impedance, Ω		Resistance, Ω	Weight of copper, kg
			High	Low	High	Low		
1	18	80	6.3	10.4	1.2	2.1	0.227	87.8
2	18	52	9.7	16.0	1.8	3.2	.349	57.1
3	21	104	4.8	8.0	0.9	1.6	.342	57.0
4	22	132	3.8	6.3	0.7	1.3	.348	56.8
5	24	208	2.4	4.0	0.5	0.8	.341	56.8
6	24	256	2.0	3.2	0.4	0.7	.277	69.9

TABLE V. - DC AND AC RESISTANCE AND WEIGHT
FOR MINIMUM NUMBER OF WIRES PER LINE

[Line Length, 150 m (total length for resistance calculation is 300 m), i.e., wires/direction.]

Number AWG	Minimum number of wires/line	R_{dc} , Ω	R_{ac} , Ω	R_p , Ω^*	Weight, kg**
18	26	0.242	0.249	0.349	57.1
21	52	.242	.244	.342	57.0
22	65	.244	.245	.343	56.4
33	833	.244	.244	.342	56.4
36	1670	.244	.244	.342	56.4

* R_p includes proximity effects.

**Weight (copper alone).

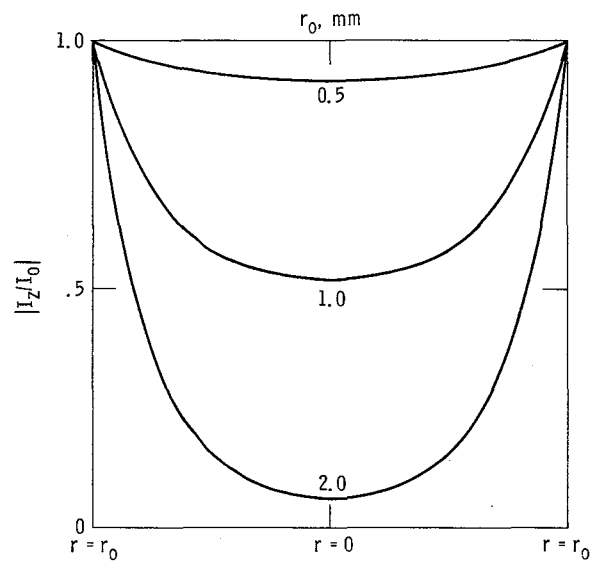


Figure 1. - Current distribution in a circular cylindrical wire of radius r_0 at 20 kHz.

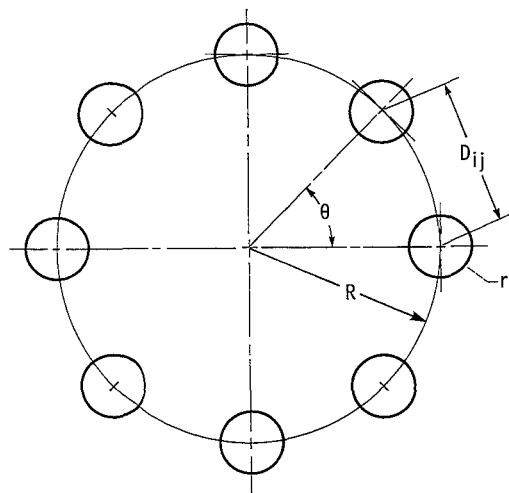


Figure 2. - Polar coordinates for CRIMPD.F, single-ring arrangement.

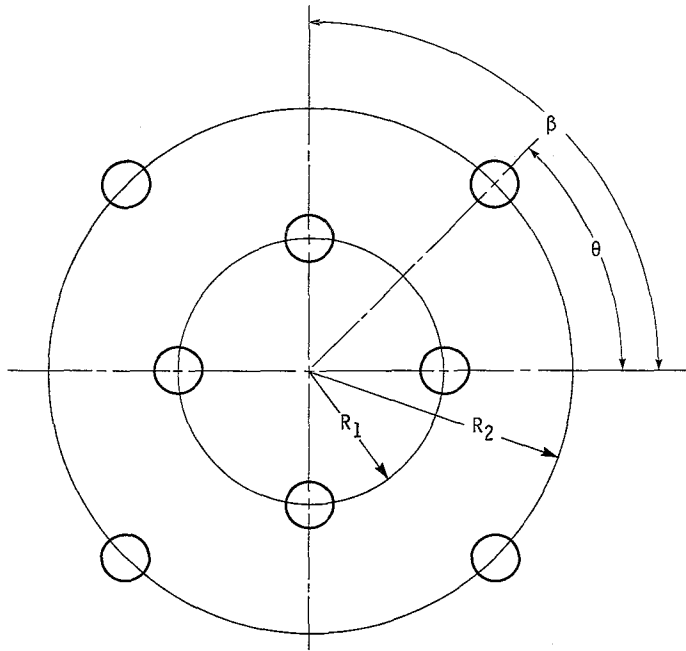


Figure 3. - Polar coordinates for CRIMPD.F, double-ring arrangement.

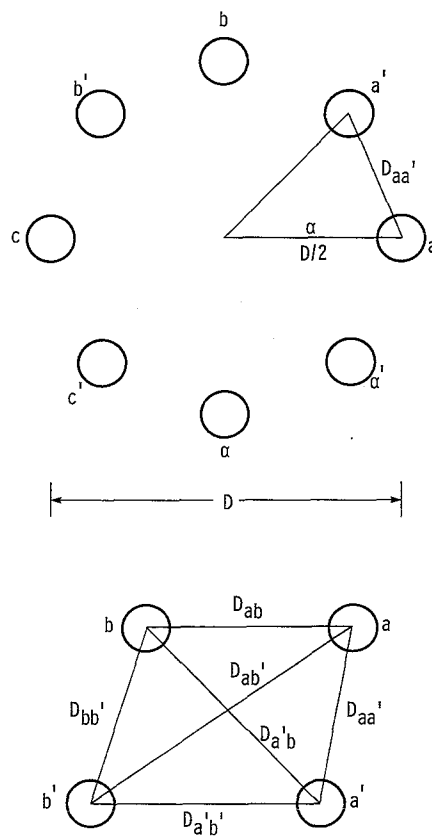


Figure 4. - Parameter definition for equation (5).
The direction of currents in the primed conductors is opposite to that in the unprimed.

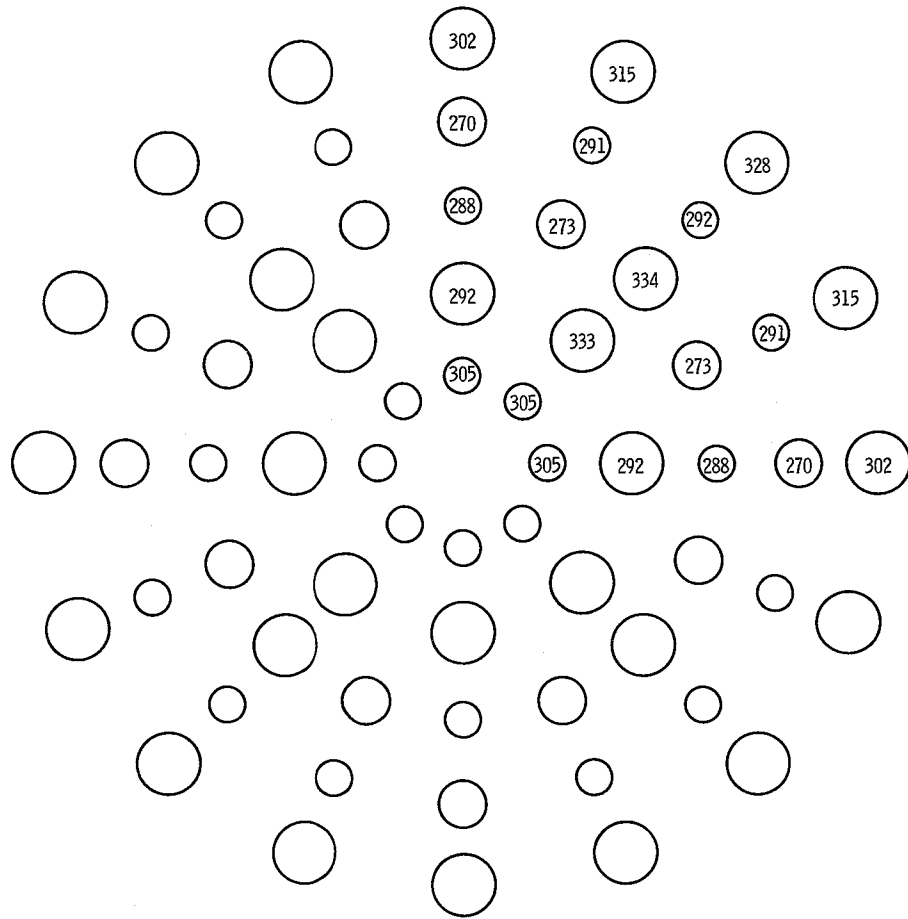


Figure 5. - 64-Wire, 5-ring line 2 (inductance values in nH/m).

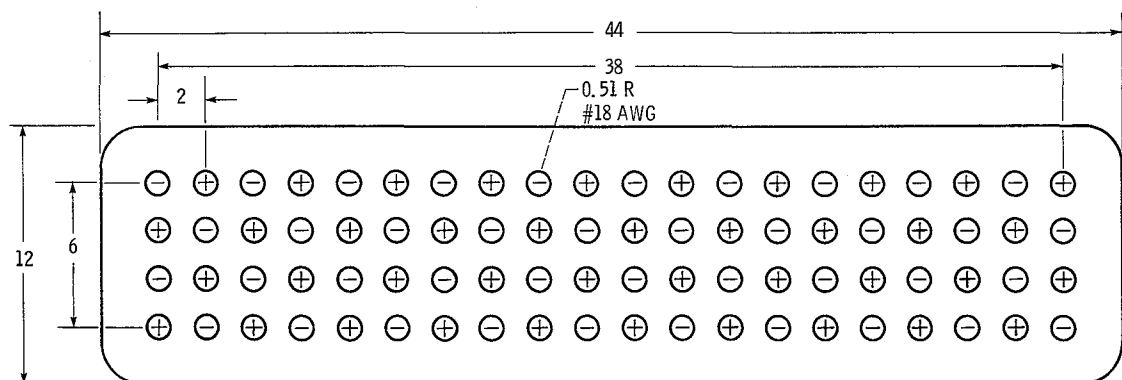
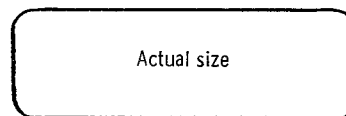


Figure 6. - 80-Wire (4x20) configuration. (All dimensions in inches.) For $\epsilon_r = 2.3$, $L = 10.42$ nH/m, $C = 2450$ pF/m, and $Z = 2.06 \Omega$. Scale: 0.2 inch = 1 mm.

Conditions	Line	x_1 , mm	y_1 , mm	Polarity	Number of conditions	Spacing, mm	Line polarity
1 to 20	1	0	0	+	20	2	Alt.
21 to 40	2	↓	2	-	↓	↓	↓
41 to 60	3		4	+			
61 to 80	4	↓	6	-	↓	↓	↓

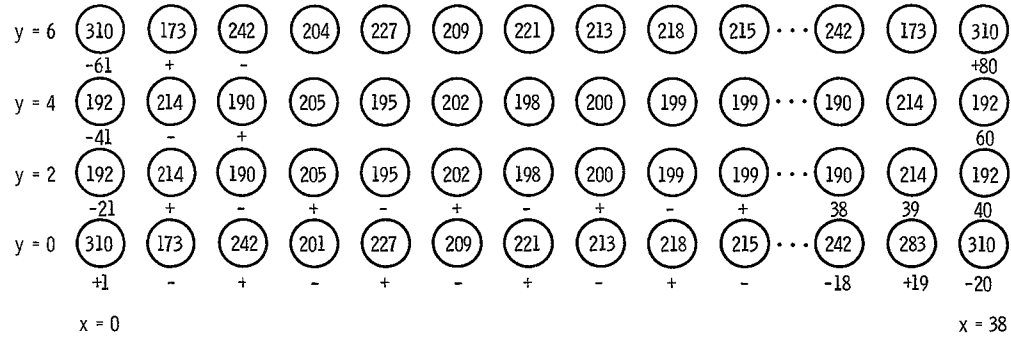


Figure 7. - 80-Wire (4x20) configuration with listing of individual self inductances in nH/m ("Inductance" method).
 $L = 10.4196$ nH/m; $C = 2.4526$ nF/m; $Z = 2.0611 \Omega$; $A = 32.6851$ mm²; $r = 0.51$ mm (#18 AWG).

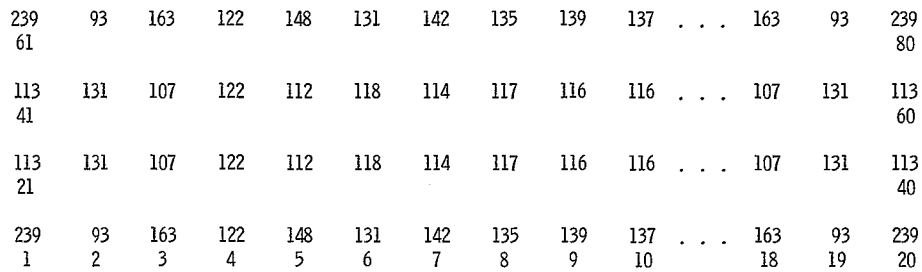


Figure 8. - 80-Wire line ("Capacitance method") individual inductances. $L = 6.3115$ nH/m; $C = 4.0490$ nF/m;
 $Z_0 = 1.2485 \Omega$; $A = 32.68$ mm²; $r = 0.51$ mm (#18 AWG).

Actual size

Condition	x_1 , mm	y_1 , mm	Spacing, mm	Polarity	Line polarity	Radii, mm
1 to 32	0	0	1.0	+	Alt.	0.25
33 to 64	↓	1.0	↓	-	↓	↓
65 to 96		2.0		+		
97 to 128		3.0		-		
129 to 160		4.0		+		
161 to 192		5.0		-		
193 to 224		6.0		+		
225 to 256	↓	7.0	↓	-	↓	↓

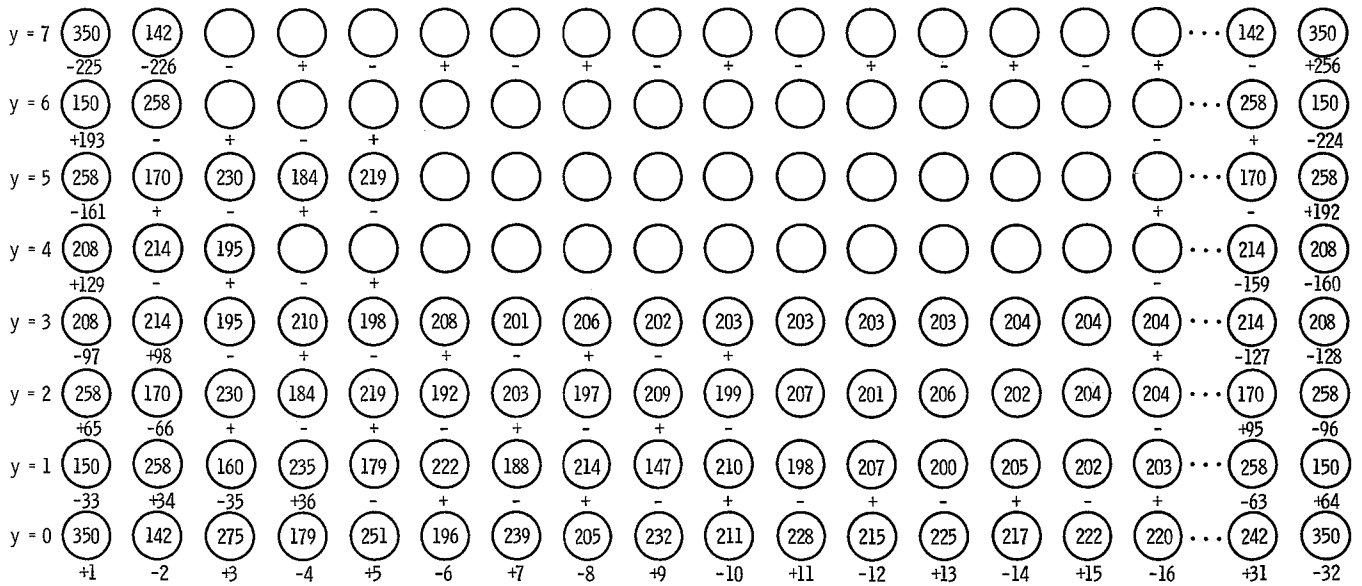


Figure 9. - 256-wire (8x32) arrangement with individual self inductances in nH/m. $L = 3.2193$ nH/m; $C = 7.9382$ nF/m; $Z = 0.6368 \Omega$; $A = 25.1327$ mm²; $r = 0.25$ mm; $\epsilon_r = 2.3$.

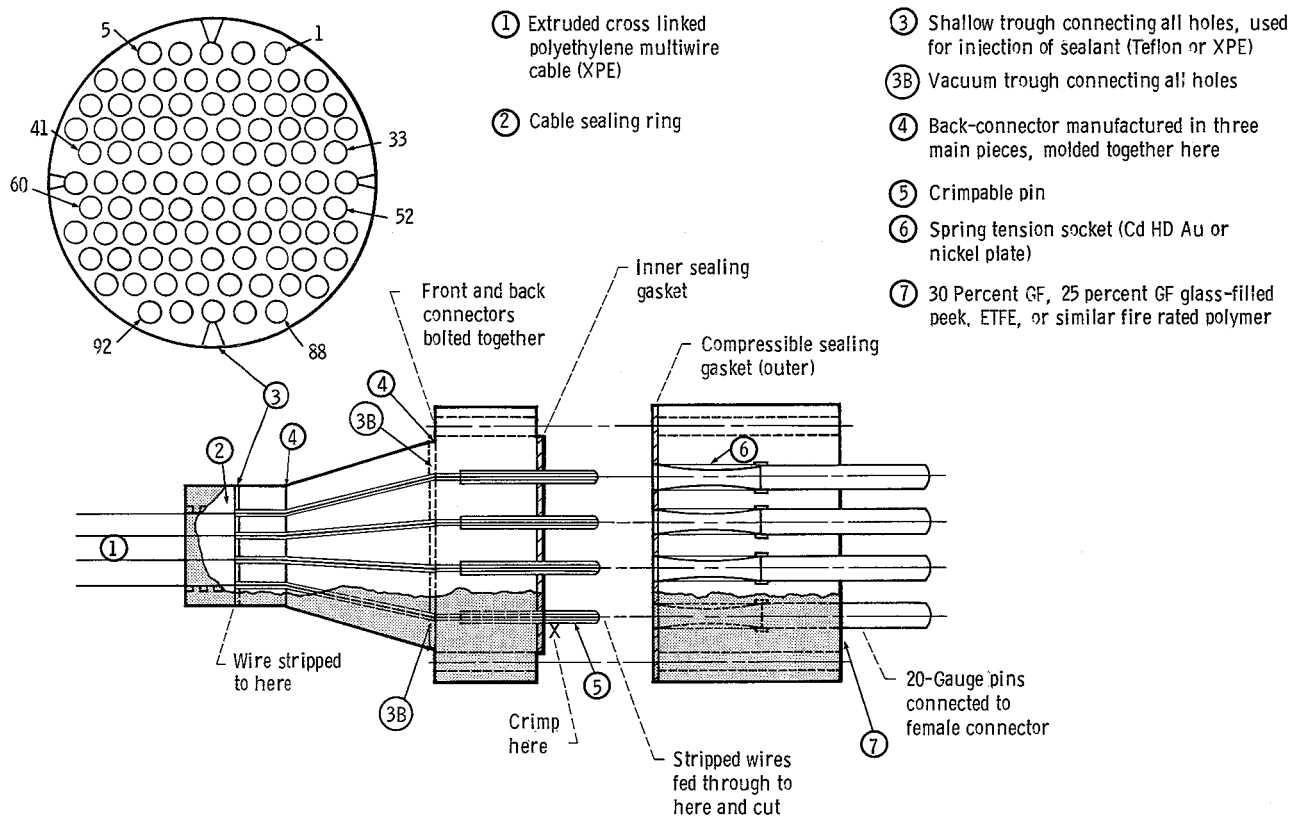
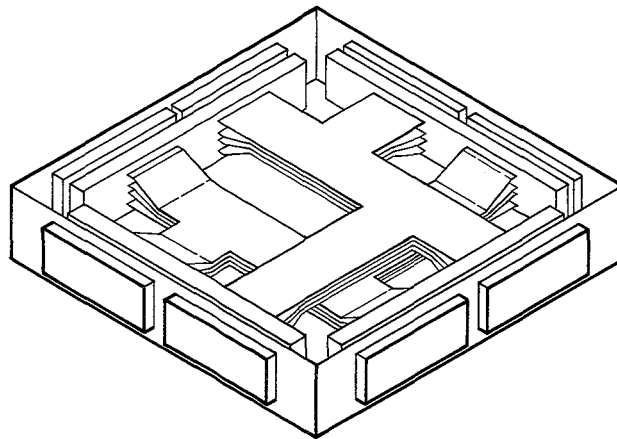
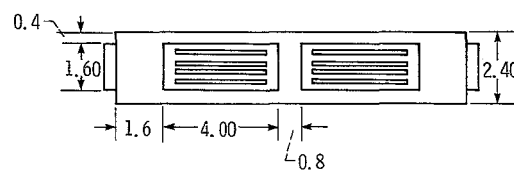
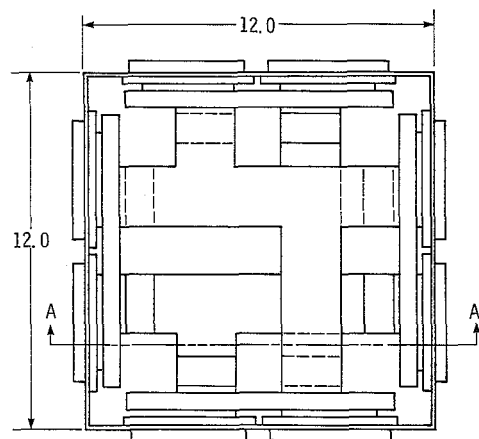


Figure 10. - Male-female junction boxes with conventional outlets.



30° Isometric view

(a) High frequency power distribution buss. Top cover not shown;
material: chassis 0.063 Al-Alloy 5053; scale, 1/2.



Section A-A'

(b) Junction-box detail. (All dimensions in inches.)

Figure 11. - Junction box.

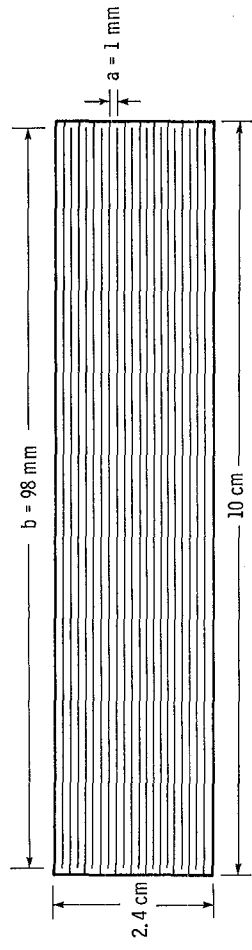
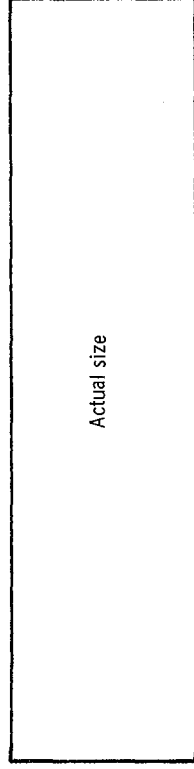


Figure 12. - Cross section of a multiple-plate transmission line. $L = 0.66 \text{ nH/m}$; $C = 35.3 \text{ nF/m}$; $Z_0 = 0.14 \Omega$; $\epsilon_r = 2.1$

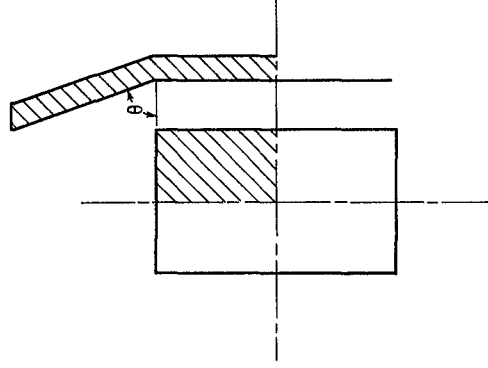


Figure 13. - Stripline configuration.



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16. Abstract A low inductance, low characteristic impedance transmission line was designed for a 20 kHz power distribution system. Several different conductor configurations were considered: strip lines, interdigitated metal ribbons, and standard insulated wires in multiwire configurations (circular and rectangular cylindrical arrangements). The final design was a rectangular arrangement of multiple wires of the same gauge with alternating polarities from wire to wire. This offered the lowest inductance per unit length (on the order of several nanohenries/meter) and the lowest characteristics impedance (on the order of one ohm). Standard multipin connectors with gold-plated elements were recommended with this transmission line; the junction boxes to be internally connected with flat metal ribbons for low inductance; and the line to be constructed in sections of suitable length. Computer programs for the calculation of inductance of multiwire lines and of capacitances of strip lines were developed.					
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